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An Experiment on Acoustic Reflection from the Sea Surface

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CONTENTS

ABSTRACT

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AN EXPERIMENT ON ACOUSTIC REFLECTION FROM THE SEA SURFACE

INTRODUCTION

A brief experiment on the forward scattering of underwater acoustic energy from the water-air interface was conducted in the Gulf of Mexico on January 25, 1968. This work was performed in support of a study of the characteristics of sonar signals propagated via the bottom-bounce path. In the bottom-bounce propagation mode, a number of multipaths exist in which the acoustic signal interacts with both the sea bottom and the sea surface. A knowledge of surface reflection loss, with its statistical variations, and a measure of signal distortion as a function of grazing angle, frequency, sea surface condition, and bearing angle relative to sea direction is important to the effective utilization of the bottom-bounce propagation path.

In this experiment an omnidirectional acoustic source was suspended at a submerged depth of 16 m from the southwest edge of the Navy Mine Defense Laboratory's offshore platform designated as Stage I. This facility is located 17.7 km seaward of Panama City, Florida, in a water depth of 32 m. A weighted receiving hydrophone was suspended at a submerged depth of 10.7 m from a small fishing boat. The amplified and filtered hydrophone signal was recorded on one FM channel of a battery-operated magnetic tape recorder. The acoustic source was programmed to project 2-cycle pulses at a frequency of 3.5 kHz and a repetition rate of 10 pulses per second. Figure 1 illustrates the experimental geometry where θ is the grazing angle and ϕ is the bearing angle relative to the wind and wave direction. The fishing boat with suspended hydrophone and receiving instrumentation repeatedly took positions on the seaward side of the platform such as to drift past the acoustic source at horizontal ranges of from 30 to 110 m. Photographs of Stage I and the fishing boat are shown in Figs. 2 and 3, respectively. Figure 4 illustrates the tracks followed by the boat during each of the six experimental runs. The black dots mark time intervals of approximately 30 sec each.

EXPERIMENTAL PROCEDURE

The source and receiving hydrophone depths were held fixed at 16 and 10.7 m, respectively. The grazing angle for the surface reflected path was a function of the horizontal range between source and receiver, whereas the direction of propagation relative to the wind and sea depended on the bearing line between source and receiver. The wind and sea maintained a constant direction estimated at 310° throughout the 2-hr duration of the experiments. A resistive-type wave staff located midway between two legs of Stage I was furnished and operated by the Mine Defense Laboratory personnel to obtain a record of wave height at that point. The bearing between the points of suspension of the hydrophone and the source was measured by means of a hand-held pelorus used on the boat. The horizontal range was determined by measuring the difference in arrival times of the direct and surface-reflected paths.

The three propagation paths that were consistently observed are diagrammed in Fig. 5. They are, in order of increasing arrival time, the direct, the surface reflected, and the bottom reflected. Figure 6 illustrates a received signal. The direct arrival is on the left, followed by the surface-reflected signal in the middle and the bottom-reflected

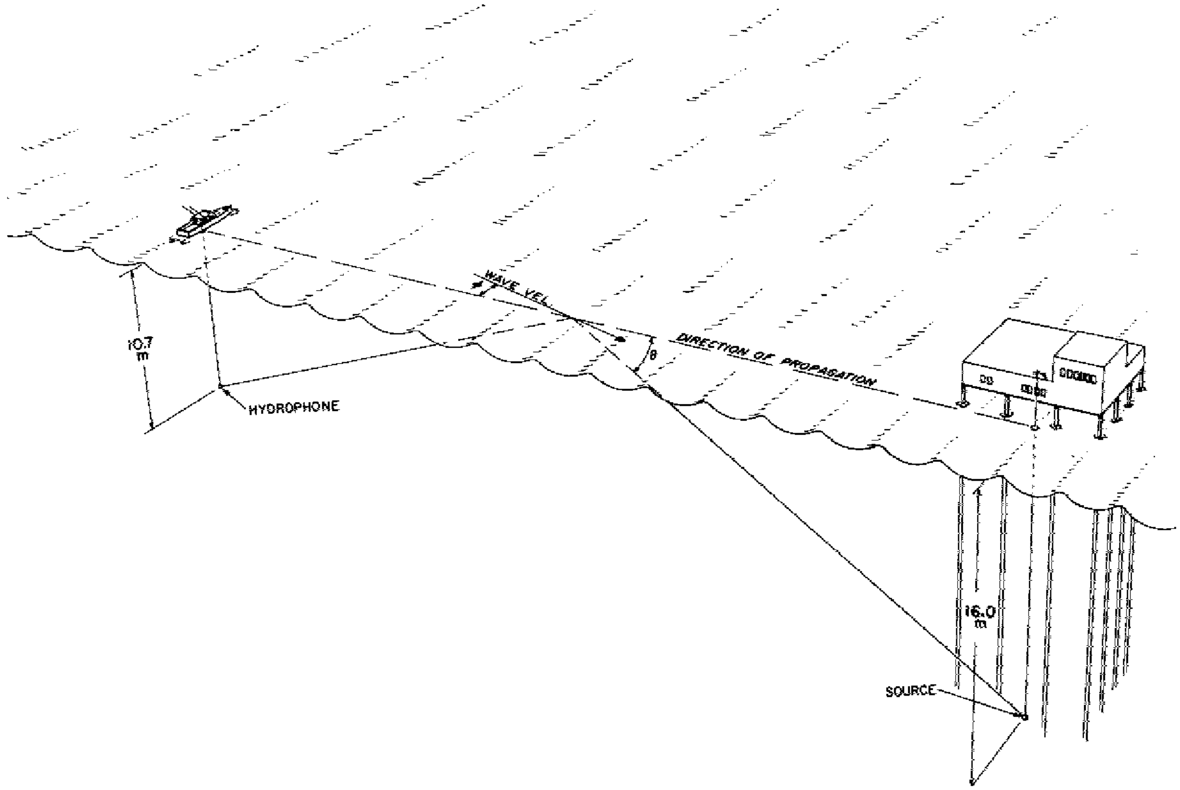

Fig. 1 – Geometry of shallow-water surface-reflection experiment. The grazing angle θ is the angle that the acoustic pulses make with the ocean surface, and ϕ is the bearing angle relative to the wind and wave direction.

signal on the right. Other paths involving multiple reflections from the boundaries were observed occasionally.

The calculated excess in propagation time of the surface-reflected signal Δt_s, and of the bottom-reflected signal Δt_b, over that of the direct path is plotted as a function of horizontal range in Fig. 7. The upper curve defines the grazing angle as a function of range and is used with the right-hand ordinate. The source and hydrophone depths were selected such that the surface-reflected arrival would fall approximately midway between the arrival times of the direct and bottom-reflected signals, with sufficient separation such that nearly all of the energy in the surface path would be free from overlap with the other paths over the range of grazing angles of interest. It can be seen that the surface-reflected path is separated in time from other paths by at least 2 msec for all grazing angles greater than 13.5 degrees.

The bandwidth of the acoustic source restricted the projected signal bandwidth. The voltage response of the Massa TR-50 transducer is plotted in Fig. 8. It can be seen that the 900-Hz bandwidth to the half-power points is considerably more narrow than the bandwidth of a 2-cycle, 3.5-kHz signal. Consequently, the source level was degraded and the pulse lengthened by the filtering action of the transducer. However, it was necessary to accept this compromise in order to obtain a sufficiently short pulse to permit time separation of the paths. Since the direct as well as the boundary-reflected signals

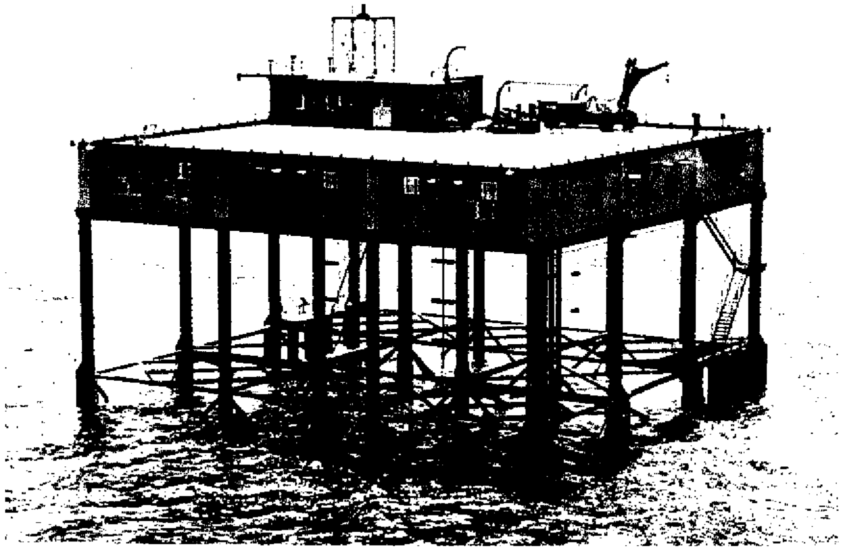

Fig. 2 - Navy Mine Defense Laboratorys offshore platform, Stage I

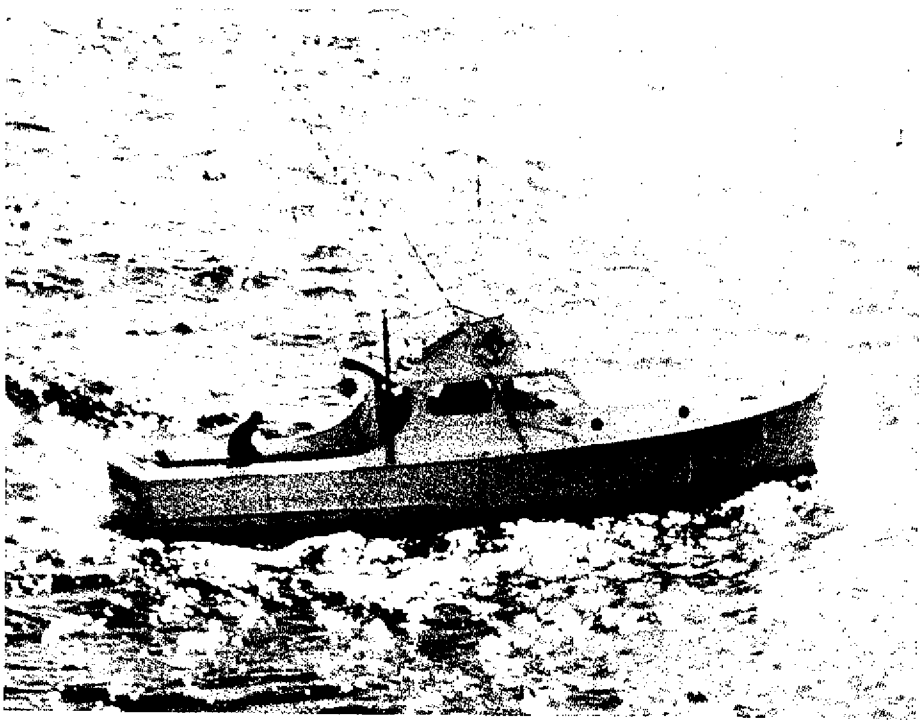

Fig. 3 - Commercial fishing boat from which the receiving hydrophone was suspended

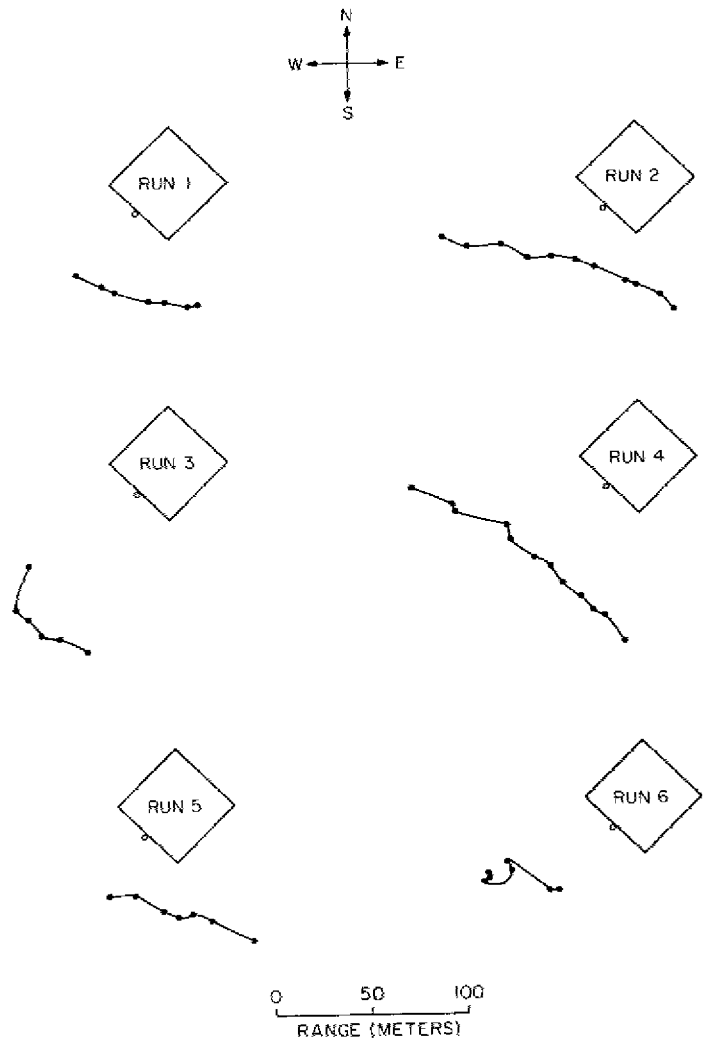

Fig. 4 - Tracks of the receiving hydrophone relative to the source platform for each of six runs. The black dots mark time intervals of about 30 sec each.

were observed for each pulse, the system was self calibrating. The electrical signal applied to the transducer was a 2-cycle, phase-locked, 3.5-kHz signal of 200-V rms amplitude. The resulting source level was approximately 76 dB relative to 1 μbar at 1 m.

Six runs were completed, with the range varying from 30 to 110 m. The resulting grazing angles and bearing relative to the sea are plotted in Figs. 9 and 10 along with the range.

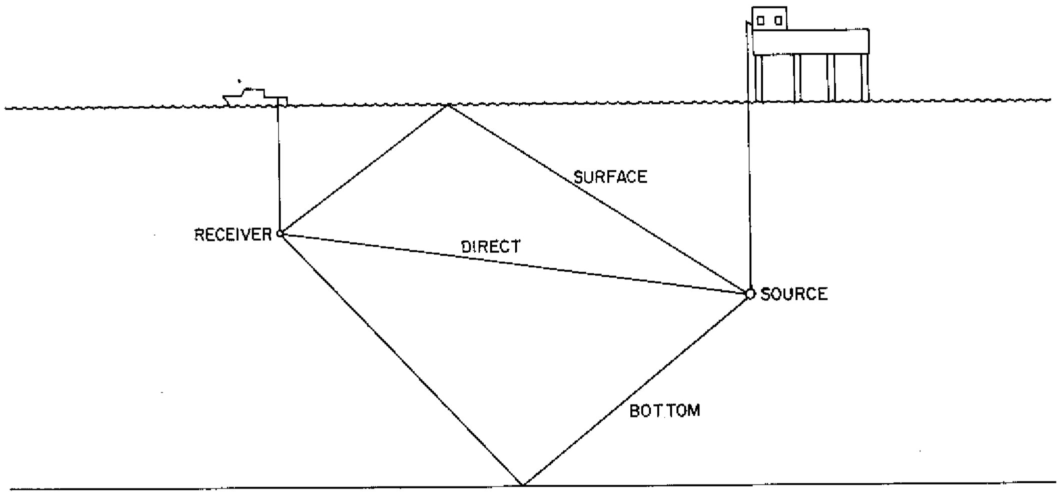

Fig. 5 - The three propagation paths observed in the surface-reflection experiment

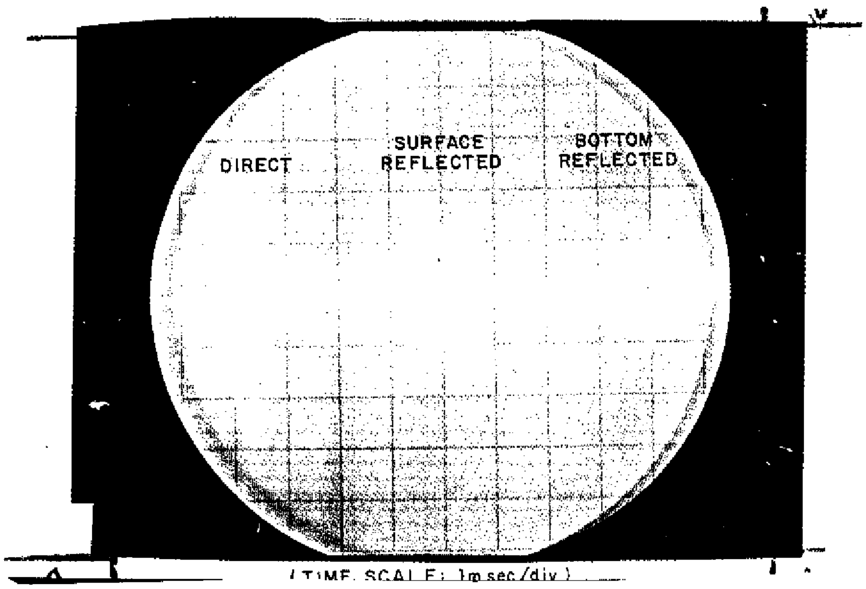

Fig. 6 - Illustration of signals received by underwater hydrophone

EXPERIMENTAL RESULTS

Surface Loss

An example of sequences of received signals of the type shown in Fig. 6 is shown in Fig. 11. The left column is a sequence of consecutive arrivals from the beginning of run number 1. The center and right-hand columns are consecutive arrivals from the middle and end of the same run, respectively. These pictures were photographed from the screen of a variable persistence oscilloscope. The persistence permits the trace of each previous pulse to be seen faintly in the background. It can be seen that the surface-reflected signal is, in most cases, an excellent replica of the direct signal, except for a

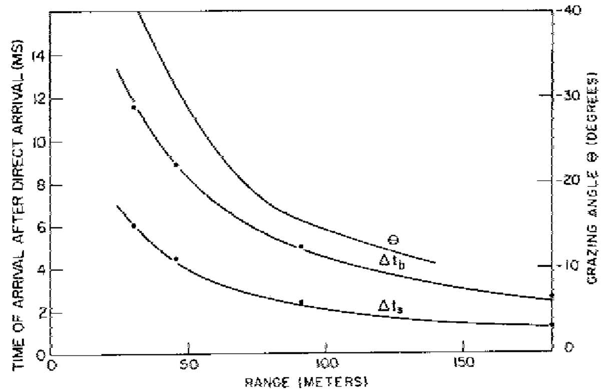

Fig. 7 - Excess propagation time for bottom- and surface-reflected paths over that of the direct path as a function of distance between receiver and source. The upper curve shows the range dependence of the grazing angle θ.

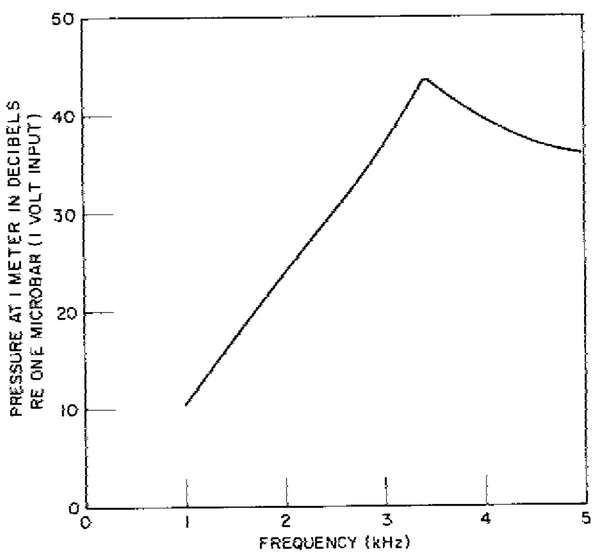

Fig. 8 - Voltage response of the Massa TR-50 transducer

variation in amplitude. Infrequently it is split into a pair of overlapping arrivals. The amplitude of the surface arrival is modulated at a rate which is slow compared to the ping repetition rate, i.e., 10 per second.

The time-varying nature of the amplitude modulation can better be seen in Fig. 12 where peak values of the surface-reflected signal level are plotted in decibels relative to lossless transmission for a 1-min interval of run number 1. The 0-dB reference is the amplitude of the direct arrival obtained by correcting for spherical spreading to the path length of the surface-reflected arrival. Surface path gains of up to 5 dB were frequently observed.

The average loss for two bearing angles relative to the sea is plotted as a function of grazing angle in Fig. 13. The bearing of 135° displays a slightly smaller loss than the

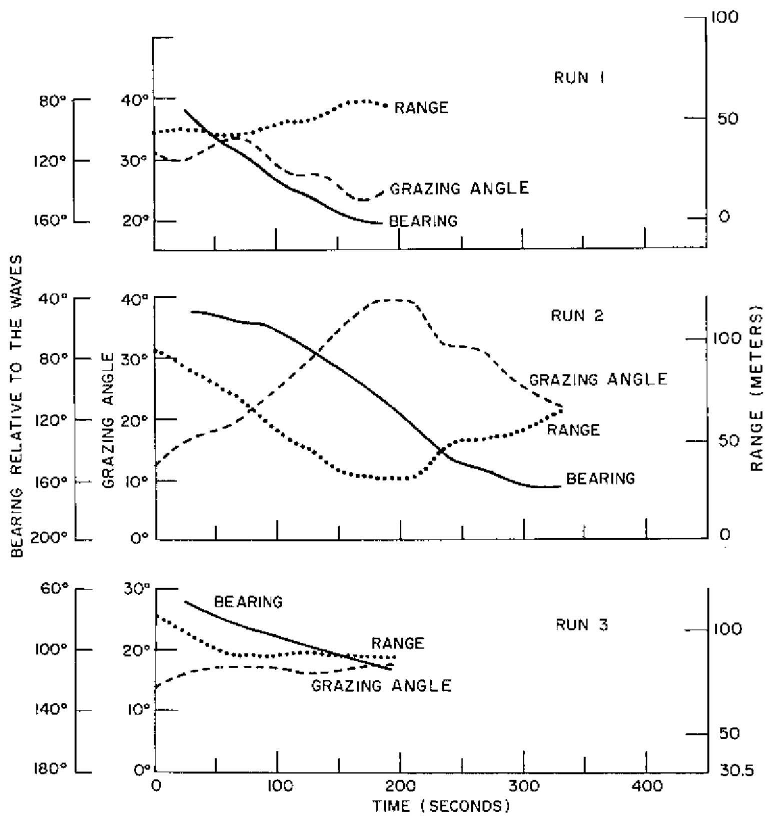

Fig. 9 - Time histories of bearing angle, grazing angle, and signal range for runs 1-3

bearing of 90°. The difference is so slight, however, that this is not considered conclusive evidence of a dependence on bearing angle.

A distribution of the surface-reflected signal amplitude relative to the direct signal for a 100-sec segment of run 6 is shown in Fig. 14. Figure 15 is the distribution of ocean wave heights taken from data furnished by the Mine Defense Laboratory. A comparison of the two figures illustrates that the reflected-signal distribution tends to be Rayleigh, while the ocean wave height distribution tends to be Gaussian.

Relative intensity spectra of the amplitude modulation of surface reflected signals were obtained by digitizing sequences of peak amplitudes, such as the one shown in Fig. 12, and storing them in a magnetic core memory. The stored sequences were then cycled out of memory repeatedly at a rate convenient for analysis, reconverted to analogue form, and analyzed with a Hewlett Packard 302A wave analyzer. The output of the analyzer was squared and smoothed to yield the spectra, shown in Fig. 16, for a 50-sec sequence of run 2 and a 100-sec sequence of run 6. The grazing angle and bearing relative to the sea for run 2 were 15° and 50°, respectively, and for run 6 were 21° and 62°, respectively. The length of the runs for a given grazing angle and bearing was dictated by the drift rate of the receiving boat. Because of the relatively short runs, there is a significant error in absolute spectral level. For a 90% confidence level, the error in the smoothed spectral value is about 50% across the band.

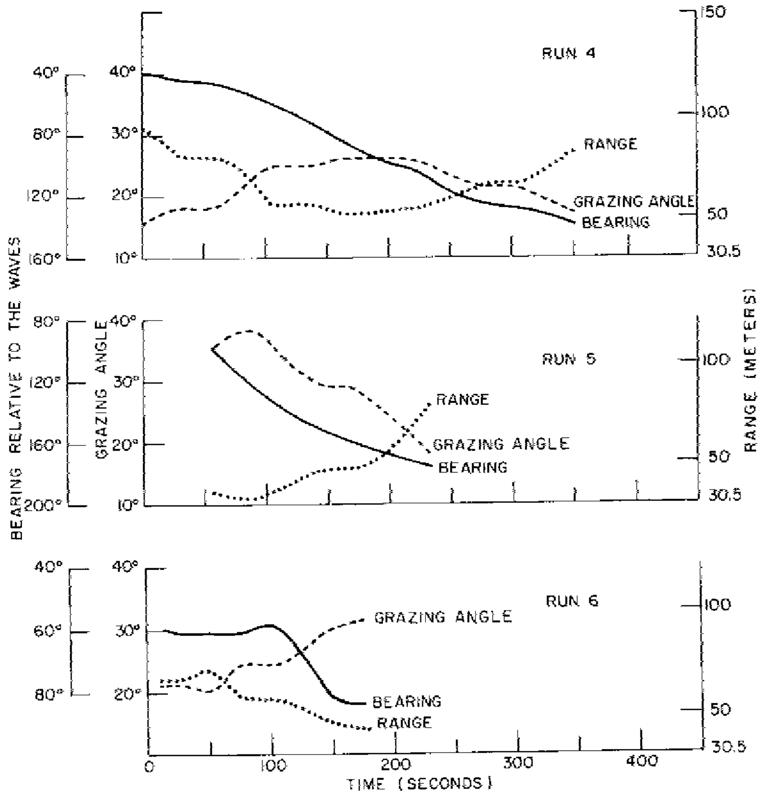

Fig. 10 - Time histories of bearing angle, grazing angle, and signal range for runs 4-6

A relative amplitude spectrum for a 10-min record of ocean wave heights, also shown in Fig. 16, was obtained in the same manner as the signal intensity spectrum, with the exception that the analyzer output was not squared. The wave heights were obtained by use of a resistance-type wave staff sampled every fifth of a second. For a 90% confidence level, the error in the smoothed ocean amplitude spectrum is about 17% across the band.

A comparison of the signal spectra and ocean wave spectrum shows that the signal amplitude varies with the same period, in this case 4 sec, as the major wave component. A secondary peak in the signal spectra at 0.62 Hz is not obviously related to the ocean wave spectrum.

Signal Distortion

Normalized cross correlations between pairs of signals arriving via the direct and surface-reflected paths were performed off-line on a linear correlator. The average of the peak value of 22 correlations was 0.95. All of the signals in this group had a direction of propagation which was approximately normal to the direction of the sea. The lowest correlation, 0.78, was obtained when the surface-reflected signal exhibited splitting, as illustrated in the first four photos of the left-hand column of Fig. 11. Correlations performed at other selected bearings relative to the direction of the sea resulted in similarly high values of coherence.

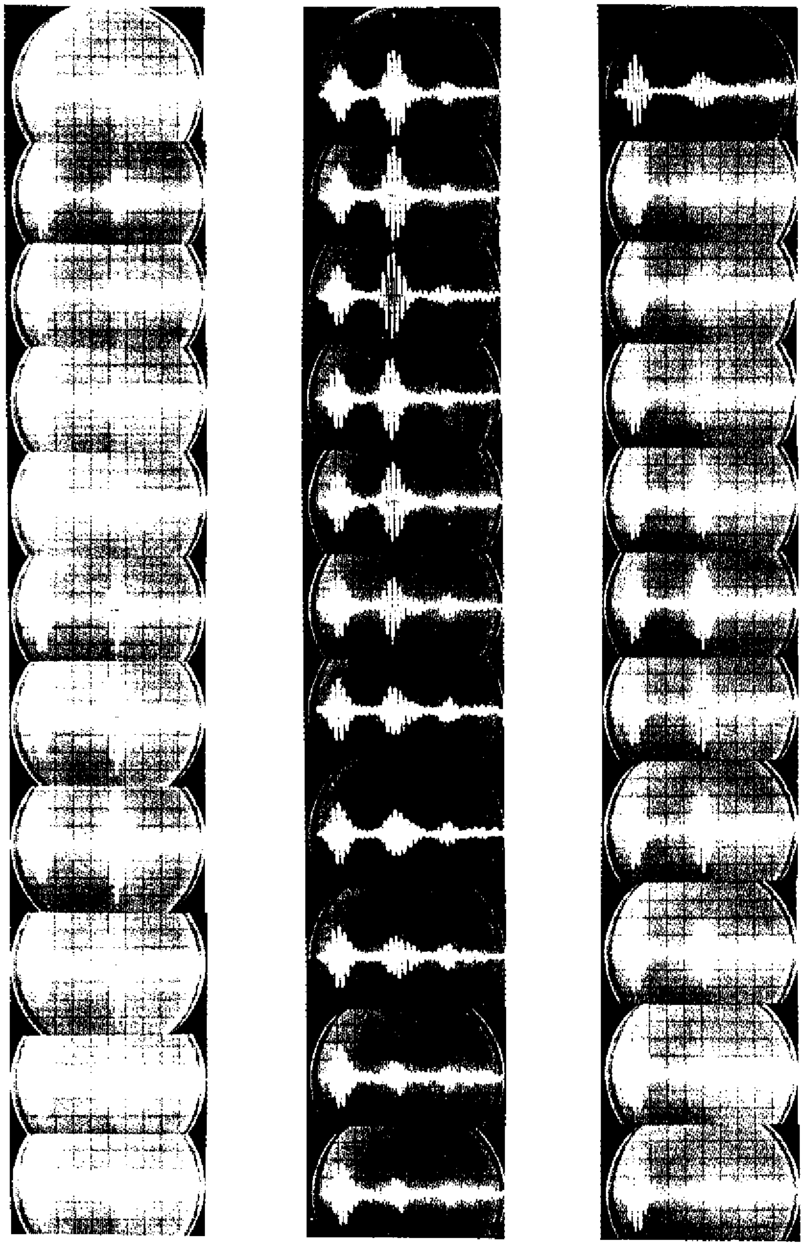

Fig. 11 - Three sequences of received signals from run 1. For each photo in a sequence, the surface-, direct-, and bottom-reflected signals appear from left to right, respectively.

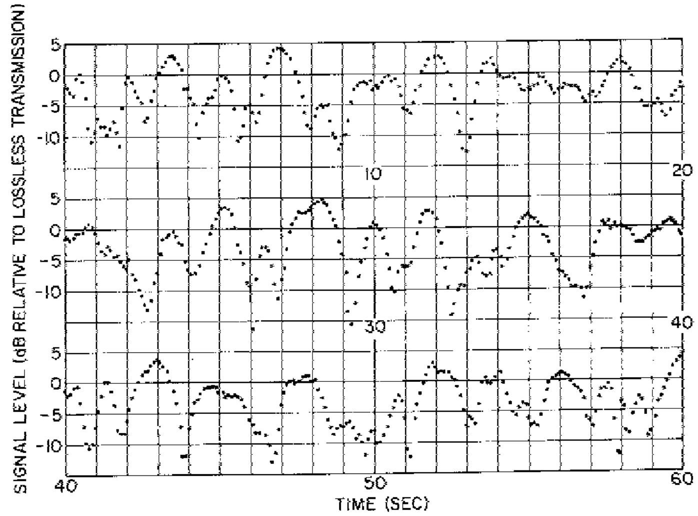

Fig. 12 - Plot of peak amplitudes of the surface-reflected signals during a one-minute interval

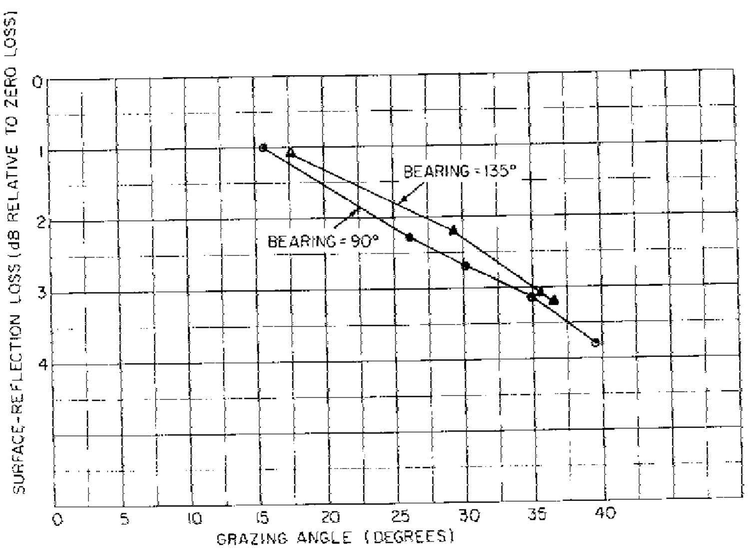

Fig. 13 - Average loss of surface-reflected signal as a function of grazing angle for bearing angles of 90° and 135°

Bottom Loss

Although the primary purpose of this experiment was to investigate surface effects, the bottom-reflected path was also insonified as shown in Fig. 5. Signals propagated via the bottom-reflected path were subject to some interference from surface reverberation which produced approximately 10% modulation with periods roughly corresponding to the amplitude modulation period of surface-reflected signals. By averaging bottom loss data over intervals of approximately 15 sec, the effect of amplitude modulation was removed to a large degree.

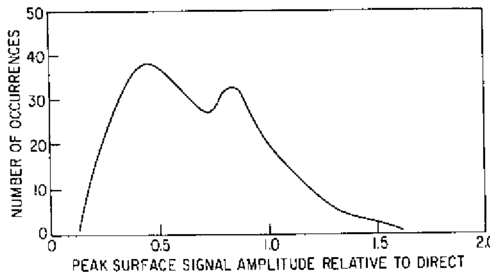

Fig. 14 - Distribution of peak amplitudes for surface-reflected signals for a 100-sec segment of run 6.

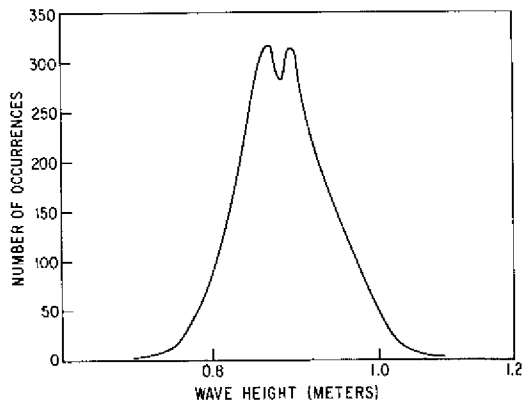

Fig. 15 - Distribution of water wave heights at the time of the experiment

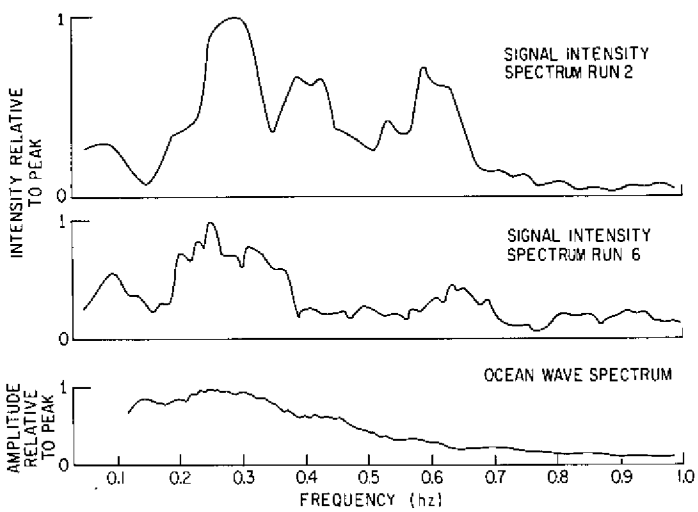

Fig. 16 - Comparison of ocean wave and acoustic signal spectra for a 50-sec segment of run 2, a 100-sec segment of run 6, and from a 10-min record of ocean wave heights

The bottom-reflection points for the six runs shown in Fig. 4 are all contained within a triangle southwest of Stage I. This area is essentially smooth sand with occasional small ripples.

Figure 17 is a plot of bottom loss as a function of grazing angle on the bottom. Each solid dot represents the average loss for approximately 15 sec of run (150 data points). The bottom loss for each data point was computed as the ratio of the amplitudes of signals received via the direct and the bottom-reflected paths with a spherical spreading correction for the ratio of the path lengths.

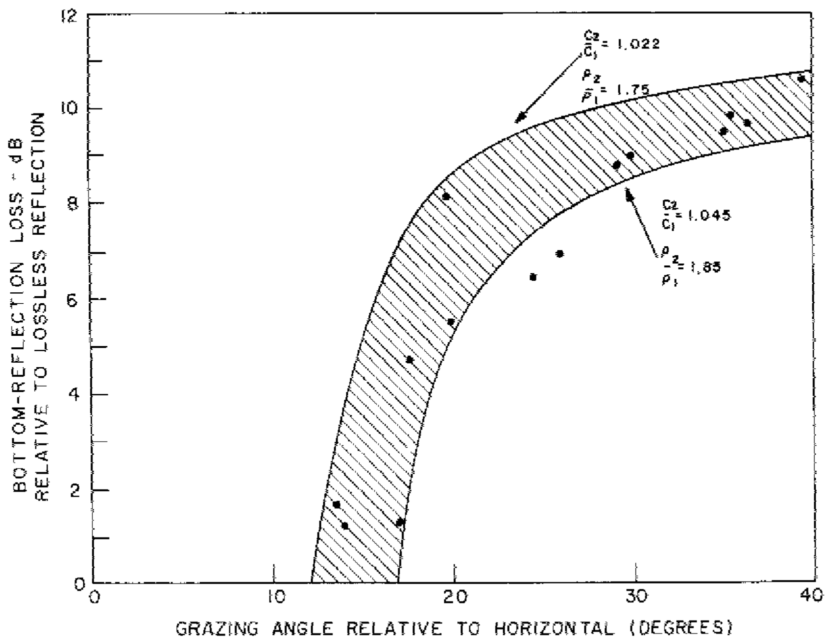

Fig. 17 - Dots represent measured reflection loss as a function of grazing angle on the ocean bottom. Solid curves, selected to bound the data points, are derived from Rayleigh's Reflection Law and Snell's Law.

These points were used to estimate the ratios of the velocity of sound in the bottom material (c_2) to the velocity of sound in water (c_1) and the corresponding density ratio ρ_2/ρ_1. This was done by estimating from the data at what angle the bottom loss would go to zero. From Fig. 17 this is shown to be between 12° and 17°. Hence we assume that the critical angle lies in that range. From Snell's Law

$$\cos \theta_c = c_1/c_2$$

we get, for $\theta_c = 12°$, the value $c_2/c_1 = 1.022$, and for $\theta_c = 17°$, we obtain $c_2/c_1 = 1.045$.

We see that in the estimated range of critical angles, the velocity ratio spread is only about 2%.

With this knowledge of the velocity ratio it is possible to estimate the density ratio. This is done with the use of Rayleigh's Reflection Law* given by

$$R = \frac{\dfrac{\rho_2}{\rho_1} - \dfrac{\left[(c_1/c_2)^2 - \cos^2\theta\right]^{1/2}}{\sin\theta}}{\dfrac{\rho_2}{\rho_1} + \dfrac{\left[(c_1/c_2)^2 - \cos^2\theta\right]^{1/2}}{\sin\theta}}$$

where θ is the grazing angle and R is the amplitude reflectivity. The boundaries of the shaded area in Fig. 17 are obtained from the above equation with the two limiting velocity ratios and the densities so picked that the shaded area covers most of the data points. It is important to note that though this technique may seem crude, the spread in the estimate of the density ratio is less than 6%.

CONCLUSIONS AND RECOMMENDATIONS

The small scale of the geometry used in this experiment is not representative of conditions normally encountered in sonar propagation paths. The measured values of surface reflection loss, therefore, should not be applied in sonar equations. The results, however, can be better related to the geometry and the environment than is usually possible in long-range propagation experiments. The data should serve, then, to test models of the mechanism of acoustic interaction with the ocean's surface and indicate those parameters of the surface which are significant in determining reflection loss. Of particular interest, in this respect, are (a) the temporal variations in loss of 20 dB, as observed in Fig. 12, (b) the relationship of the period of the variations to sea spectra, and (c) surface reflection gains of up to, but not exceeding, 5 dB, which were frequently observed.

Additional environmental data is needed to make the results of this type of experiment optimally useful for model development. In particular, more comprehensive information concerning surface configuration and velocity is needed than is afforded by a single-point measurement of wave height. Detailed velocity profiles along the propagation path would permit calculation of refractive spreading loss to refine the accuracy of surface loss measurements. Also, a more stable receiving platform to eliminate effects of hydrophone motion would be desirable.

*Officer, C.B., "Introduction to the Theory of Sound Transmission," New York: McGraw-Hill, 1958.

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